DESIGN AND DEVELOPMENT OF SOLAR PV FED PMSM DRIVEN WATER PUMPING SYSTEM

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by

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CERTIFICATE

It is certified that the thesis entitled "**Design and Development of Solar PV Fed PMSM Driven Water Pumping System**," being submitted by **Mr. Shadab Murshid** for award of the degree of **Doctor of Philosophy** in the Department of Electrical Engineering, Indian Institute of Technology Delhi, is a record of the student work carried out by him under my supervision and guidance. The matter embodied in this thesis has not been submitted for award of any other degree or diploma.

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ABSTRACT

The utilization of solar photovoltaic (PV) energy in water pumping is conservative particularly in isolated regions where the cost of transmission of power is either impractical or exorbitant. In this research work, various topologies for solar PV array fed water pumping are developed using a permanent magnet synchronous motor (PMSM) motor drive. A high efficiency PMSM substantially reduces the size of PV array and hence its installation cost. Moreover, its high power factor results in a reduced capacity of the used voltage source inverter (VSI). Besides these, unlike an induction motor, the speed of a PMSM is not limited by power frequency. This leads to a reduced size of the motor.

A reduced sensor based simple, efficient and cost-effective PMSM drive is investigated with sensor-less field oriented control. The estimation of rotor speed and position, is carried out through the stator flux. The system possesses a maximum power point tracking (MPPT) of the PV array by introducing a DC-DC boost converter between the PV array and a VSI, feeding the motor. The work is extended towards an elimination of DC-DC converter and a single stage PV array PMSM drive is also investigated for water pumping.

The recurrence in PV power generation leads to an unreliable water pumping in a PV based pumping system. This problem is aggravated when there is a bad climatic condition. In all these conditions, the system is underutilized as the pump is not operated at its full capacity and sometime leads to complete shutdown. This problem is resolved through the introduction of an auxiliary power source in the form of a battery storage. In addition to it, an attempt is made for integrating unidirectional and bidirectional converters to the utility grid. The bidirectional power flow control based topology offers an additional merit of feeding power to the utility grid by the installed PV array, in case the water pumping is not required. The prime attention is to achieve an uninterrupted and full volume of water delivery irrespective of the operating

conditions, whether day or night. These proposed techniques with PV array provide a practical solution for electricity generation and an economic liberty for the consumer through sale of electricity.

All these proposed configurations are modeled and simulated in MATLAB/Simulink environment by using Simpower system toolbox to study the performance during various environmental conditions realized by change in insolation and the operability of the system is justified during starting, dynamic and steady state conditions. Simulated results are verified through test results obtained from hardware implementation using a developed prototype in the laboratory. The applicability and commercial potential of proposed systems are justified by their in depth analysis based on efficiency, cost, simplicity and performance.

सारांश

पानी के पंपिंग में सौर फोटोवोल्टिक (पीवी) ऊर्जा का उपयोग विशेष रूप से पृथक क्षेत्रों में रूढ़िवादी है जहां बिजली के संचरण की लागत या तो अव्यावहारिक या अतिरंजित है। इस शोध कार्य में, एक स्थायी चुंबक तुल्यकालिक मोटर (पीएमएसएम) ड्राइव का उपयोग करके सौर पीवी सरणी पानी पंपिंग के लिए विभिन्न टोपोलॉजी विकसित की जाती हैं। एक उच्च दक्षता पीएमएसएम पीवी सरणी के आकार को काफी कम कर देता है और इसलिए इसकी स्थापना लागत। इसके अलावा, इसके उच्च शक्ति कारक का उपयोग वोल्टेज स्रोत इन्वर्टर (वीएसआइ) की कम क्षमता के परिणामस्वरूप होता है। इन के अलावा, एक प्रेरण मोटर के विपरीत, एक पीएमएसएम की गति बिजली आवृत्ति द्वारा सीमित नहीं है। इससे मोटर का आकार कम हो जाता है।

एक कम सेंसर आधारित सरल, कुशल और लागत प्रभावी पीएमएसएम ड्राइव की जांच सेंसर-कम क्षेत्र उन्मुख नियंत्रण के साथ की जाती है। रोटर की गति और स्थिति का अनुमान स्टेटर फ्लक्स के माध्यम से किया जाता है। इस प्रणाली में मोटर को खिलाते हुए पीवी सरणी और वीएसआइ के बीच डीसी-डीसी बूस्टर कनवर्टर को पेश करके पीवी सरणी का अधिकतम पावर प्वाइंट ट्रैकिंग (एमपीपीटी) होता है। कार्य को डीसी-डीसी कनवर्टर के उन्मूलन की ओर बढ़ाया जाता है और पानी पंप करने के लिए एक एकल चरण पीवी सरणी पीएमएसएम ड्राइव की भी जांच की जाती है।

पीवी बिजली उत्पादन में पुनरावृत्ति एक पीवी आधारित पंपिंग सिस्टम में एक अविश्वसनीय पानी पंपिंग की ओर जाता है। खराब जलवायु की स्थिति होने पर यह समस्या बढ़ जाती है। इन सभी स्थितियों में, सिस्टम को कम कर दिया जाता है क्योंकि पंप अपनी पूर्ण क्षमता पर संचालित नहीं होता है और कभी-कभी पूर्ण बंद हो जाता है। इस समस्या को एक बैटरी स्टोरेज के रूप में एक सहायक बिजली स्रोत की शुरूआत के माध्यम से हल किया जाता है। इसके अलावा, उपयोगिता ग्रिड में यूनिडायरेक्शनल और बिडायरेबल कन्वर्टर्स को एकीकृत करने का प्रयास किया जाता है। द्विदिशीय विद्युत प्रवाह नियंत्रण आधारित

टोपोलॉजी स्थापित पीवी सरणी द्वारा उपयोगिता ग्रिड को बिजली खिलाने का एक अतिरिक्त गुण प्रदान करता है, अगर पानी पंप करने की आवश्यकता नहीं है। मुख्य ध्यान ऑपरेटिंग दिवस की परवाह किए बिना, चाहे दिन हो या रात, जल वितरण की निर्बाध और पूर्ण मात्रा प्राप्त करना है। पीवी सरणी के साथ ये प्रस्तावित तकनीक बिजली उत्पादन के लिए एक व्यावहारिक समाधान और बिजली की बिक्री के माध्यम से उपभोक्ता के लिए आर्थिक स्वतंत्रता प्रदान करती है।

इन सभी प्रस्तावित विन्यासों को मैटलैब / सिमुलिंक परिवेश में मॉडल और सिम्युलेटेड किया गया है, जो इनसोलेशन में परिवर्तन द्वारा महसूस की गई विभिन्न पर्यावरणीय स्थितियों के दौरान प्रदर्शन का अध्ययन करने के लिए सीमपावर सिस्टम टूलबॉक्स का उपयोग करता है और सिस्टम की संचालनशीलता शुरू, गतिशील और स्थिर राज्य स्थितियों के दौरान उचित है। प्रयोगशाला में एक विकसित प्रोटोटाइप का उपयोग करके हार्डवेयर कार्यान्वयन से प्राप्त परीक्षण परिणामों के माध्यम से नकली परिणाम सत्यापित किए जाते हैं। दक्षता, लागत, सादगी और प्रदर्शन के आधार पर गहराई से विश्लेषण द्वारा प्रस्तावित प्रणालियों की प्रयोज्यता और व्यावसायिक क्षमता को उचित ठहराया जाता है।

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LIST OF ABBREVIATIONS

AC	Alternating Current
ADC	Analog to Digital Converter
ANN	Artificial Neural Network
BIS	Bureau of Indian Standards
BLDC	Brushless DC
BEMF	Back EMF
BES	Battery Energy Source
BESS	Battery Energy Storage System
CCM	Continuous Conduction Mode
CEC	Clean Energy Council
CER	Clean Energy Regulator
CPU	Central Processing Unit
CSI	Current Source Inverter
DAC	Digital to Analog Converter
DC	Direct Current
DSP	Digital Signal Processor
DTC	Direct Toque Control
EMC	Electro-Magnetic Compatibility
EMF	Electro-Motive Force
EMI	Electro-Magnetic Interference
FEC	Front End Converter
FL	Fuzzy Logic
FLL	Frequency Locked Loop
FOC	Field Oriented Control
GI	Generalized Integrator
IC	Integrated Circuit
IEC	International Electro technical Commission
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistor
IM	Induction Motor
INC	Incremental Conductance

IS	Indian Standard
KF	Kalman Filter
LPF	Low Pass Filter
MMGI	Mixed Multi-resonant Generalized Integrator
MNRE	Ministry of New & Renewable Energy
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
NASA	National Aeronautics and Space Administration
PFC	Power Factor Correction
PI	Proportional Integral
PLL	Phase Locked Loop
PMSM	Permanent Magnet Synchronous Motor
PQ	Power Quality
P&O	Perturb and Observe
ISOGI	Improved
PV	Photo-Voltaic
PWM	Pulse Width Modulation
RE	Renewable Energy
RMS	Root Mean Square
SHE	Selective Harmonic Elimination
SOGI	Second Order GI
SRM	Switched Reluctance Motor
STC	Standard Test Condition
SWP	Solar Water Pumping
SyRM	Synchronous Reluctance Motor
TF	Transfer Function
THD	Total Harmonic Distortion
UPF	Unity Power Factor
UVT	Unit Vector Template
VSC	Voltage Source Converter
VSI	Voltage Source Inverter
WPS	Water Pumping System

LIST OF SYMBOLS

a	Overloading factor
C_{dc}	Capacitor at the DC bus of VSI (μF)
C_{pv}	Capacitor across the PV array (μF)
C_f	Capacitor of the R-C ripple filter (μF)
C_1, C_2	Capacitor of the Vienna Rectifier (μF)
D	Duty Ratio of the boost converter
e_α, e_β	Stationary reference frame estimated back EMF (V)
f_{sw}	Switching frequency of IGBT switch of boost converter (Hz)
m	Modulation index
N_{rated}	Rated speed of the PMSM (rpm)
p	Number of pole pairs
i_α, i_β	Stationary reference frame stator currents (A)
i_a, i_b, i_c	Stator currents of PMSM (A)
i_{aref}, i_{bref}, i_{cref}	Reference stator currents of PMSM (A)
i_{gref}	Reference grid current (A)
i_g, v_g	Sensed grid current (A) and voltage (V)
i_{ga}, i_{gb}, i_{gc}	Sensed grid currents (A)
I_{bat}, V_{bat}, P_{bat}	BESS current (A), voltage (V) and power (W)
I_{batref}	Reference current of BESS (A)
I_{cmax}	Maximum charging current of the BESS (A)
I_{dref}, I_{qref}	Reference direct and quadrature axis currents of PMSM (A)
I_{dc}	Current at the DC link of VSI (A)
I_{mpp}, V_{mpp}, P_{mpp}	Solar PV array current (A), voltage (V) and power (W) at MPP
I_{pv}, V_{pv}, P_{pv}	Solar PV array current (A), voltage (V) and power (W)
I_{sc}, V_{oc}	Solar PV array short circuit current (A) and open circuit voltage (V)
K_{vf}, K_{if}	Voltage and current safety factor
L	Inductor of the boost converter
L_f	Interfacing inductor (mH)
P_m	Rated power of the PMSM (W)
qv_f	Fundamental quadrature component (V)
qv_{3f}, qv_{5f}, qv_{7f}	3^{rd}, 5^{th} and 7^{th} harmonic quadrature components (V)

R_f	Resistance of the R-C ripple filter (Ω)
t_s	Settling time (s)
S	Solar insolation (W/m^2)
S_{bu},S_{bl}	Switching pulses for bidirectional converter
S_{I1}-S_{I6}	Switching pulses for three phase VSI
S_{pfc}	Switching pulses for boost PFC converter
T_e, T_m	Electromagnetic and mechanical torque of PMSM (Nm)
T_{eest}	Estimated torque of PMSM (Nm)
T_{eref}	Reference torque of PMSM (Nm)
u_p	Unit template
v_α, v_β	Stationary reference frame stator voltages (V)
V_{dc}	DC link voltage (V)
V_{dcref}	Reference DC link voltage (V)
V_{dcerr}	DC link voltage error (V)
v_f	Fundamental in-phase component (V)
v_{ga}, v_{gb}, v_{gb}	Estimated grid phase voltages (V)
v_{gab}, v_{gbc}	Sensed grid line voltages (V)
V_{grms}	R.M.S. grid voltage (V)
v_{3f}, v_{5f}, v_{7f}	3rd, 5th and 7th harmonic in-phase component (V)
V_t, V_{th}	Terminal and threshold voltage (V)
W_g	Weight component of the grid current (A)
ψ_α, ψ_β, ψ_r	Flux components (V.s)
θ_{eest}	Estimated rotor position (rad)
ζ	Damping factor
ω_{err}	Speed error (rad/s)
ω_{eest}	Estimated electrical speed of the PMSM (rad/s)
ω_g	Grid frequency (rad/s)
ω_{mest}	Estimated mechanical speed of the PMSM (rad/s)
ω_{rated}	Rated speed of the PMSM (rad/s)
ω_{ref}	Reference speed of the PMSM (rad/s)